PARAMETERIZED UPDRAFT MASS FLUX AS A PREDICTOR OF CONVECTIVE INTENSITY

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1. INTRODUCTION

Mesoscale models are used routinely to provide guidance in forecasting severe convection. For example, examination of output from the Environmental Modeling Center's (EMC's) Eta (Black 1994) and RUC-2 (Benjamin et al. 1998) models is a firmly entrenched part of the forecast preparation process at the Storm Prediction Center (SPC), especially for the convective outlook product. In recent years, additional mesoscale models have become available and these are also consulted by SPC forecasters on occasion.

What sort of information do forecasters expect to glean from these various models? These models are often utilized for their predictions of synoptic-scale patterns, wind fields, etc. In addition, the models are capable of predicting mesoscale circulations and local thermodynamic structures that can provide valuable clues as to where convection might initiate and how it might evolve. As for the actual prediction of deep convection, however, forecasters receive nothing more than the same information that has been provided for many years from coarser-resolution models. Specifically, they receive parameterized convective rainfall totals, typically accumulated over 3-6 h time periods.

It is unfortunate that operational models provide only this single measure of convective intensity because accumulated precipitation is a superficial and often ambiguous reflection of the vigor of convection. Moreover, numerous potentially revealing characteristics of convection are computed internally in these models, but are not provided as part of standard model output.

As part of our testing of experimental models at the National Severe Storms Laboratory (NSSL) and the SPC, we have been providing SPC forecasters with additional diagnostic terms that are routinely computed in the Kain-Fritsch (KF - 1993) convective parameterization scheme (CPS). This CPS is used in place of the operational Betts-Miller-Janjic scheme in our twice-daily runs of the Eta model at NSSL. The KF output field that has received the most favorable response from SPC forecasters is a normalized "updraft mass flux" (UMF*) predicted by the scheme. The magnitude of this field provides a measure of how much mass this CPS transports through cloud base as part of its internal procedure for stabilizing the local environment. As such, it provides a unique prediction of convective intensity, a measure that is not always well correlated with the precipitation rate determined by the KF scheme or other CPSs.

The purpose of this paper is to clarify how UMF* is computed and how it depends on various thermodynamic parameters in an input sounding. In section 2 we describe the procedure used by the KF scheme to remove instability in a convecting grid column and how UMF* fits into this procedure. The sensitivity of UMF* to various characteristics of input soundings is shown in section 3 followed by a short summary in section 4.

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2. A DESCRIPTION OF THE KAIN-FRITSCH CONVECTIVE PARAMETERIZATION

The KF CPS is based on fixed-point observations of the changes that occur in tropospheric thermodynamic structure as a result of deep moist convection (i.e., Fritsch et al. 1976). Specifically, it is designed to simulate a vertical rearrangement of mass that allows the atmosphere to eliminate CAPE. This rearrangement occurs in the scheme through three vertical transport mechanisms: a moist convective updraft, a moist convective downdraft, and a dry branch of ascent or descent that is assumed to occur locally (i.e., within a grid column) to compensate for the moist drafts. The third component is necessary for 2 reasons: 1.) A grid column in a model is divided up into many vertical layers, and mass must be conserved in each layer during processing by the CPS; 2.) each grid *column* is completely closed off from its neighbors within the CPS, so mass compensation must be accomplished within the column.

The first task of the KF scheme is to evaluate potential *updraft-source layers (USLs)* to determine whether convection can be initiated and, if so, from what model layers unstable air would originate. The normalized UMF value that we provide as model output is the fraction of the mass in the USL that must be extracted in order to eliminate CAPE, i.e.,

$$UMF* = \frac{UMF_{USL} \times \tau_c}{M_{USL}} \quad , \qquad (1)$$

where UMF_{USL} is the updraft mass flux (kg s^{-1}) at the top of the USL, as determined by the parameterization, τ_c is the convective time period (s) and M_{USL} is the mass of air in the USL (kg).

Potential USLs are evaluated as follows. Beginning at the surface, vertically adjacent model layers are mixed until the depth of the mixture is at least 50 mb. This combination of adjacent model layers comprises the first potential USL. The mean thermodynamic characteristics of this mixture are computed, along with the temperature and height of this "parcel" at its lifting condensation level (LCL). The parcel is given a perturbation (as described in Kain and Fritsch 1992) and the parcel buoyancy equation is used to determine whether it can reach its level of free convection (LFC) . If it can reach the LFC and continue to rise beyond a specified minimum depth (typically 3-4 km), this USL is identified as the source for air that flows through cloud base. If not, the base of the potential updraft source layer is moved up one model layer and the procedure is repeated. This process continues until either the first suitable source layer is found, or the sequential search has moved up above the lowest 300 mb of the atmosphere, where the search is terminated. Since only one source layer is allowed to contribute in a given convective cycle (τ_c ~ 30 mins.) the parameterized updraft derives most of its mass from the lowest layer that is ~50 mb deep and satisfies the above criteria. It is important to note that, since each grid column is considered independently in this procedure, the total amount of mass withdrawn from a source layer is limited to the amount of mass in that layer initially.

Once an USL has been identified, stabilization of a grid column is accomplished by the three vertical transport mechanisms Each of the mechanisms plays an important role, as described below.

2.1 Moist convective updrafts

Convective updrafts in the KF scheme are represented using an enhanced formulation of a steady-state entraining plume, the details of which can be found in Kain and Fritsch (1990). The plume model is based on Lagrangian parcel theory, which can be used to estimate updraft thermodynamic characteristics at each model level. Cloud top is established as the level where vertically-integrated buoyancy goes to zero. Most of the condensate produced in the updraft is converted to precipitation (although some detrains into the environment) and a portion of this precipitation (quantified below) is used to drive an evaporatively cooled downdraft. The remaining precipitation arrives at the surface, giving the parameterized precipitation rate.

Updraft mass accumulates and modifies the environment only where detrainment is determined to occur. In many environments, almost all of the detrainment occurs within 100-200 mb of cloud top, so significant direct modification of the environment by the parameterized updraft often occurs primarily near cloud top. Over most of the cloud layer, the parameterized updraft warms and dries the environment *indirectly*. Specifically, since the mass conservation imposed by the scheme requires the air surrounding the updraft to subside, parameterized warming and drying in the cloud layer is usually dominated by vertical advection of θ and q_v in the clear-air environment.

2.2 Moist convective downdrafts

Moist downdrafts are also represented using an entraining-plume model. In the version of the KF scheme used in the Eta model, a parameterized downdraft begins with zero mass flux ~150 mb above the top of the USL and it entrains mass as a linear function of pressure-depth as it approaches the top of this layer. Thus, when it reaches the top of the USL, its θ_e value is equal to a mass-weighted mean of the environmental θ_e in the model layers between the top of the USL and ~150 mb above. As the downdraft enters the USL, entrainment stops and detrainment begins. The detrainment layer extends downward to the point where parcels lose negative buoyancy or the surface is reached, and detrainment is distributed evenly over this layer. The relatively low θ_e air typically found in the downdraft entrainment layer replaces some of the unstable air that is extracted from the USL and this exchange is often the dominant mechanism of stabilization in the parameterization (see the stabilization closure description below).

Efficient stabilization of the environment is favored when θ_e in the downdraft is much lower than θ_e in the updraft source layer. But, of course, this also depends also on how *much* downdraft mass is available for detrainment. In the version of the KF scheme currently being used in the Eta model, the *downdraft* mass flux (DMF) at the top of the detrainment layer (also the top of the USL) is specified as a fraction of the UMF according to:

$$\frac{DMF_{USL}}{UMF_{USL}} = 2 \times (1 - \overline{RH}) \qquad (2)$$

where $\overline{RH}$ is the mean relative humidity in the downdraft *entrainment* layer. So, for a given updraft, more downdraft mass detrains when the air just above the USL is dry. Conversely, downdraft mass flux decreases as air in this layer approaches saturation. A third important factor is the depth of the detrainment layer. Effective lowering of θ_e in the USL is favored when downdraft detrainment is concentrated in that layer. This would be the case, for example, when the USL is in contact with the surface. On the other hand, if the USL is elevated, it may end up sharing downdraft air with layers below, making stabilization of the USL less efficient.

The amount of precipitation that is necessary to drive the downdraft through evaporative cooling effects is determined by the above mass-flux constraints and a specified relative humidity profile in the downdraft. In the version of the KF scheme currently being used in the Eta model, the downdraft is assumed to remain nearly saturated above the top of the USL, then dry out at a rate of 20% relative humidity per km below this level. In extreme cases (*i.e.*, high USL and dry air in the downdraft entrainment layer) all of the precipitation generated by the updraft evaporates in the downdraft and the DMF is limited by the specified relative humidity and available precipitation.

2.3 Local compensating vertical motions

Once updraft and downdraft mass fluxes (of opposite sign) are determined, local compensating vertical motions are imposed so that the net vertical mass flux at any level in the column is zero. For a full-tropospheric cloud, this typically means that compensating subsidence produces heating and drying in the upper half of the cloud layer. Subsidence rates may be weaker in the layer where DMF is non-zero (or compensating *upward* motion may even occur if -DMF>UMF), but typically the compensating motion is downward throughout the column. While this almost always induces warming and drying tendencies at each level, it also represents a vertical advection of θ_e, so it can augment downdraft effects by transporting lower θ_e air into the USL if θ_e is decreasing with height just above the USL.

2.4 Method and implications of satisfying the KF closure

These representations of updraft, downdraft, and compensating environmental motions allow the KF scheme to generally characterize the convective fluxes that would be likely to develop in a given unstable environment and they provide us with a first guess at the magnitude of the fluxes. The relative magnitudes of the different branches of the circulation are not allowed to change from this point, but the strength of the entire circulation typically requires an adjustment in order to remove CAPE in the column.

A convective time period is estimated (KF 1993) and the impact of the first-guess mass fluxes acting over this time period is computed. The CAPE value for the modified USL and cloud environment is then determined. Through an iterative procedure, the strength of the circulation is adjusted until at least 90% of the CAPE is eliminated by this rearrangement of mass. The CAPE reduction is accomplished by the combined effects of lowering θ_e in the USL and warming the environment aloft

In order to demonstrate how the KF scheme operates and the sensitivity of computed UMF* to variations in sounding structure, we utilize an analytical sounding generator derived from Weisman and

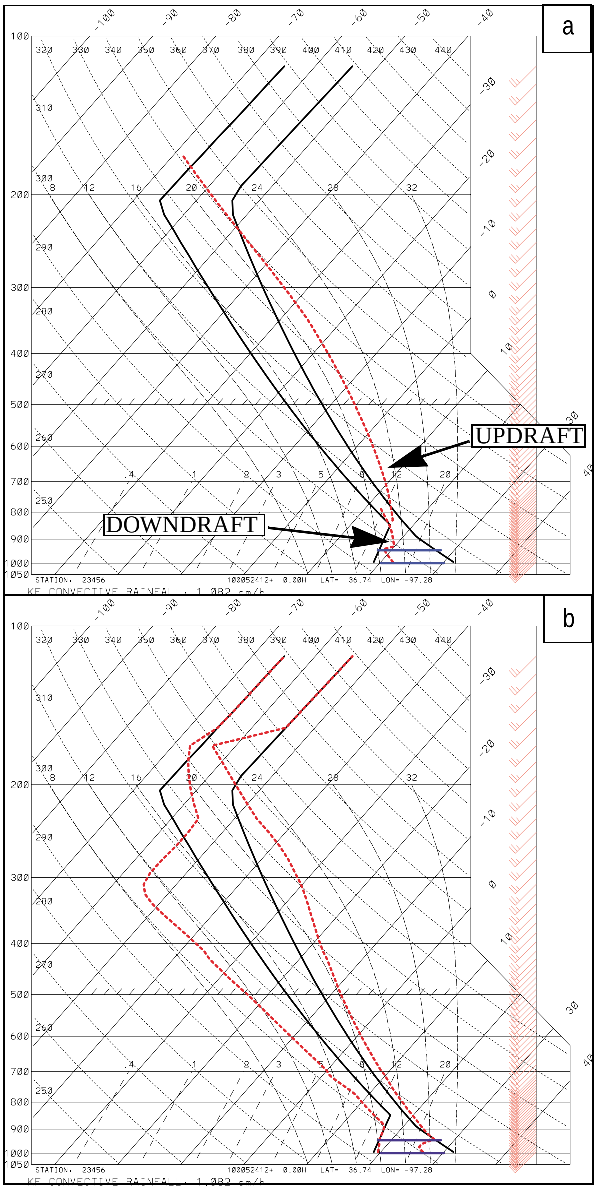

Fig. 1. An idealized sounding with thick dashed lines overlaid to show (a) the updraft and downdraft paths and (b) the modified sounding resulting from mass rearrangements, both predicted by the KF scheme.

Klemp (1982). Fig. 1a shows a sample thermodynamic profile from this routine, along with the updraft and downdraft paths predicted by the scheme for this environment indicated. Note that the updraft path deviates from a moist adiabat as a result of entrainment. The downdraft approaches the USL (denoted by thick parallel horizontal lines) with the mean wet-bulb temperature of its source layer (~775-925 mb). At this point it changes temperature abruptly because cooling due to melting precipitation is applied. Below this point (i.e., in the detrainment layer) its θ_e value does not change, but its lapse rate increases because it is assumed to become sub-saturated. Modification of this environment by the scheme is indicated in Fig. 1b. Note

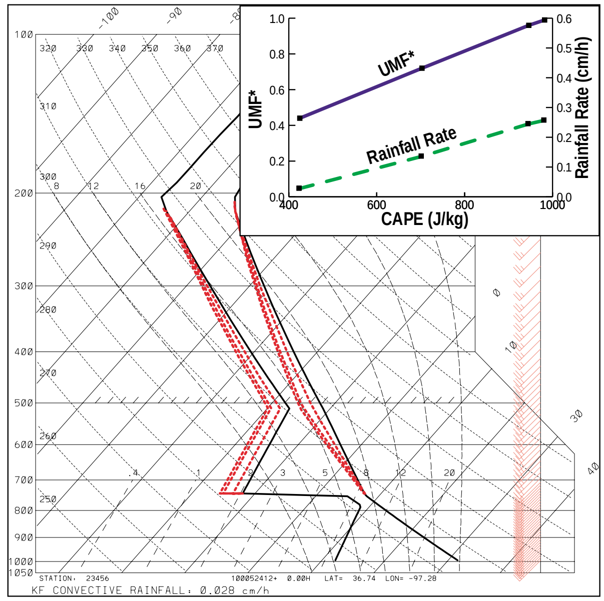

Fig. 2. Idealized soundings showing variations in CAPE achieved by changing the lapse rate between 850 and 500 mb. Inset plot shows UMF and parameterized rainfall rate as a function of the CAPE changes*

the strong cooling from downdraft detrainment in the USL (and from updraft detrainment above ~230 mb) and the warming and drying through most of the cloud layer due to subsidence in the clear air.

3. UMF* AS A DIAGNOSTIC QUANTITY

With the sounding generator routine, thermodynamic profiles can be systematically modified to evaluate the sensitivity of UMF* to vertical structure. For comparison, we also plot the rainfall rate as a function of these different structures. For each of the soundings shown below, the USL is the lowest ~50 mb layer.

3.1 Sensitivity to CAPE

UMF* can be quite sensitive to CAPE, but it depends on the vertical distribution of CAPE. For example, Fig. 2 shows a series of soundings in which CAPE was modified by increasing the lapse rate between ~850 and 500 mb. It is important to recognize that in this series of modifications, θ_e values remain constant in both the USL and the downdraft source layer. As the inset plot in Fig. 2 indicates, CAPE increases from about 450 to 975 J kg^{-1} as the lapse rate is varied over the range shown on the Skew-T diagram. UMF* is shown to be quite sensitive to these modest changes in CAPE, increasing from about .44 for the lowest CAPE value to 1.0 for the highest. The parameterized rainfall rate increases as a similar monotonic function of CAPE, from about 0.05 cm h^{-1} to .27 cm h^{-1}.

UMF* responds very differently when CAPE is enhanced by increasing moisture (and θ_e) in the USL, while keeping θ_e constant in the downdraft source layer. For example, the inset in Fig. 3 shows that UMF* changes very little as CAPE values go from about 450 to 2700

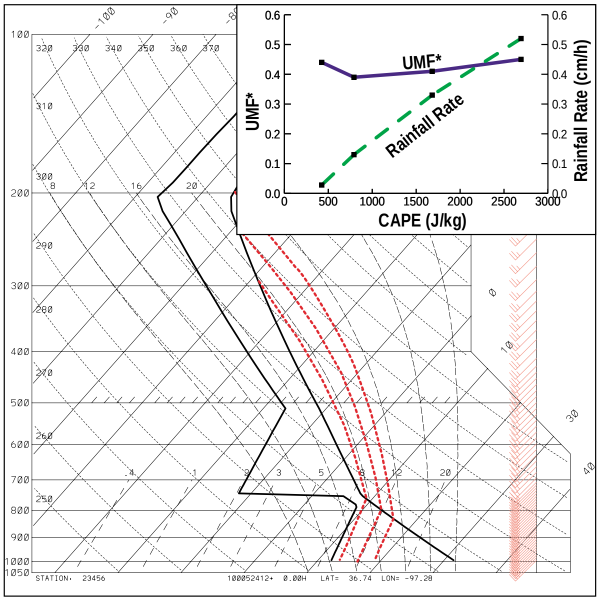

Fig. 3. Idealized soundings beginning with the same sounding as in Fig. 2, but with CAPE increased as a function of USL moisture increases rather than cloud-layer cooling. Inset shows UMF and parameterized rainfall rate as a function of CAPE.*

J kg^{-1}. In contrast, the rainfall rate again increase monotonically with increasing CAPE.

These results suggest that diagnostic UMF* values are very sensitive to the vertical distribution of CAPE. In particular, UMF* responds strongly when environmental lapse rates increase just above cloud base. This is a desirable sensitivity because, for a given CAPE value, high lapse rates in the lower part of the cloud layer appear to favor severe convection (e.g., see Blanchard 1998).

3.2 Sensitivity to downdraft θ_e

As suggested in Section 2, the primary mechanism of stabilization with the KF scheme is often replacement of high-θ_e in the USL with low-θ_e air from the parameterized downdraft. Consequently, one would expect that stabilization would be more efficient with lower θ_e values in the downdraft. Fig. 4 confirms this sensitivity. In the series of soundings shown here the USL is again the lowest ~50 mb, but the well-mixed layer near the surface is only ~100 mb deep, so the downdraft (drawing mass from the ~150 mb layer above the USL) is able to tap into the low-θ_e air above the boundary layer. As the mean θ_e of the downdraft source layer is increased from ~325K to ~343K (by increasing moisture in the elevated mixed layer), UMF* increases from about .35 to 1.0. Rainfall rate also increases with this change, reaching almost 2 cm h^{-1} as downdraft stabilizing capacity weakens. It is also worth noting that the CAPE value in each of these soundings is ~4300 J kg^{-1}, so relatively low UMF* values can be diagnosed even with very high CAPE.

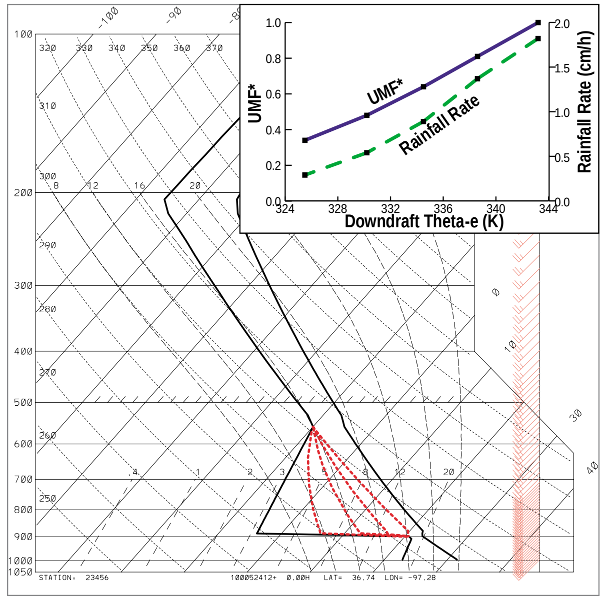

Fig. 4. Idealized soundings showing variations in elevated-mixed-layer moisture with constant CAPE. Inset shows UMF and parameterized rainfall rate as a function of changes in downdraft θ_e that result from the moisture variations.*

4. SUMMARY

In experimental runs of the Eta model at NSSL, normalized updraft mass flux (UMF*) is generated as a routine output field to help highlight areas where severe convection is possible. UMF* is determined by the KF convective parameterization and has been received favorably by SPC forecasters. UMF* is sensitive to CAPE, but it appears to discriminate between “short, fat CAPE”, as opposed to “tall, skinny CAPE”, which is a desirable sensitivity because concentration of parcel buoyancy in the lower troposphere appears to favor severe convection. Because of this sensitivity, UMF* appears to be a valuable alternative to parameterized convective rainfall rate, which can be an ambiguous indicator of convective intensity.

5. REFERENCES

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